

Azimuthal correlations of forward dijets in d+Au collisions at RHIC

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Abstract.

Measuring correlations between forward dijets in deuteron-gold collisions at RHIC will further test the Color Glass Condensate (CGC) picture of the nuclear wavefunction at small- x , which successfully predicted the suppressed production of high- p_T particles at forward rapidities in d+Au collisions: $R_{dA} < 1$. I present predictions for the correlation in azimuthal angle between forward dijets in the CGC framework, with both multiple scatterings and non-linear QCD evolution at small- x taken into account.

1. Forward particle production in p+A type collisions

Forward particle production in proton-nucleus collisions allows one to investigate the non linear QCD dynamics of high-energy nuclei with a probe well understood in QCD. Indeed, while such processes are probing small-momentum (small- x) partons in the nuclear wavefunction, only high-momentum partons of the proton contribute to the scattering. For instance, in the case of two-particle production, the longitudinal fraction of momenta probed in the proton (x_p) and in the nucleus (x_A) are given by

$$\sqrt{s} x_p = |k_1| e^{y_1} + |k_2| e^{y_2}, \quad \sqrt{s} x_A = |k_1| e^{-y_1} + |k_2| e^{-y_2} \quad (1)$$

where k_1, k_2 and y_1, y_2 are the transverse momenta and rapidities of the final state particles. Therefore, with $\sqrt{s} \gg |k_1|, |k_2|$ and forward rapidities $y_1, y_2 > 0$, the process features $x_p \lesssim 1$ and $x_A \ll 1$, meaning that the scattering involves a well-known dilute hadron p and dense nuclear target A , whose non-linear QCD dynamics can be studied.

The Color Glass Condensate (CGC) framework was quite successful in describing single inclusive particle production at forward rapidities in d+Au collisions at RHIC [1, 2]. In this work, we focus on forward inclusive two-particle production $pA \rightarrow h_1 h_2 X$ with h_1 and h_2 detected in the proton direction, and in particular on correlations in azimuthal angle between the produced hadrons [3]. We argue that the second d+Au run at RHIC gives the opportunity to carry out these measurements, and check the relevance of the CGC picture of high-energy nuclei at RHIC energies.

In the following, the $pA \rightarrow h_1 h_2 X$ cross-section is derived and used in the context of d+Au collisions to predict the azimuthal angle distribution.

2. Forward dijet production

The kinematic ranges for forward particle measurements at RHIC are such that $x_p \sim 0.5$ and $x_A \sim 10^{-4}$. Therefore the dominant partonic subprocess is initiated by valence quarks in the proton and, at lowest order in α_s , the $pA \rightarrow h_1 h_2 X$ cross-section is obtained from the $qA \rightarrow qgX$ cross-section, the quark density in the proton and the appropriate hadron fragmentation functions.

By contrast, the nucleus A , whose partons with small fraction of momentum (mainly gluons) are described by a CGC, cannot be described by a single gluon density. The $qA \rightarrow qgX$ cross section is instead expressed in terms of correlators of Wilson lines (which account for multiple scatterings), with up to a six-point correlator [4]. Assuming a Gaussian CGC wavefunction allows to express all the correlators in terms of a single function $\Gamma(r, x_A)$, related to the variance of the Gaussian distribution [5]. In the large- N_c limit, the non-linear QCD evolution at small- x_A is included through the Balitsky-Kovchegov (BK) evolution [6, 7] of $e^{-\Gamma}$.

The cross-section for the production of the quark-gluon dijet (with respective transverse momenta q_\perp and k_\perp and rapidities $y_q > 0$ and $y_k > 0$) then reads [4]:

$$\frac{d\sigma^{pA \rightarrow qgX}}{d^2k_\perp d^2q_\perp dy_k dy_q} \propto \frac{\alpha_s C_F}{4\pi^2} x_p q(x_p, \Delta) \sum_{\lambda\alpha\beta} \left| I_{\alpha\beta}^\lambda(z, k_\perp - \Delta; x_A) - \psi_{\alpha\beta}^\lambda(z, k_\perp - z\Delta) \right|^2 F_{x_A}(\Delta) \quad (2)$$

with $\Delta = k_\perp + q_\perp$ and $1/z - 1 = |q_\perp| e^{y_q - y_k} / |k_\perp|$. The different components in (2) are:

- the quark distribution function in the proton $q(x_p, \Delta)$ (we are working with $|\Delta| \gg \Lambda_{QCD}$); in principle the gluon initiated processes $gA \rightarrow q\bar{q}X$ and $gA \rightarrow ggX$ should also be included, they would contribute for smaller values of x_p .
- the Fourier transform of the two-point (dipole) correlator $F_{x_A}(\Delta)$, also called the unintegrated gluon distribution function, given by

$$F_{x_A}(\Delta) = \int \frac{d^2r}{(2\pi)^2} e^{-i\Delta \cdot r} e^{-\Gamma(r, x_A)} ; \quad (3)$$

contrary to the dilute proton, the CGC cannot be described only by its gluon distribution $F_{x_A}(\Delta)$, the k_T -factorization formula is not applicable [8, 9] (it would if there was no other x_A dependence in (2), as in single gluon production [10, 11]).

- the k_T -factorization breaking terms (whose simple form is due the use of a Gaussian CGC wavefunction) $\sum_{\lambda\alpha\beta} \left| I_{\alpha\beta}^\lambda(x_A) - \psi_{\alpha\beta}^\lambda \right|^2$ with

$$I_{\alpha\beta}^\lambda(z, k_\perp; x_A) = \int d^2q_\perp \psi_{\alpha\beta}^\lambda(z, q_\perp) F_{x_A}(k_\perp - q_\perp) ; \quad (4)$$

as the valence quark emits the virtual gluon (the associated wavefunction is $\psi_{\alpha\beta}^\lambda$ where λ, α and β are polarization and spin indices) it interacts coherently with the dense small- x gluons in A , which modifies the $q \rightarrow qg$ splitting.

In practice, the initial condition $\Gamma(r, x_0) = r^2 Q_{s_0}^2 \ln[e + 1/(r^2 \Lambda_{QCD}^2)]/4$ is used with the choice $x_0 = 0.01$ and the initial saturation scale $2\pi Q_{s_0}^2 = 2 \text{ GeV}^2$. Then $e^{-\Gamma}$ is evolved with the BK equation, allowing to compute (3), (4) and the cross-section (2).

3. Dijet correlations in azimuthal angle

We will now use the inclusive two-particle spectrum (2) to investigate the process $dAu \rightarrow h_1 h_2 X$, with $\sqrt{s} = 200$ GeV. In particular we shall study the $\Delta\phi$ spectrum where $\Delta\phi = \phi_1 - \phi_2$ is the difference between the azimuthal angles of the measured particles h_1 and h_2 . We will study the normalized $\Delta\phi$ distribution

$$\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi} \equiv \left(\frac{d\sigma^{hT \rightarrow h_1 h_2 X}}{dp_{T_1} dp_{T_2} dy_1 dy_2} \right)^{-1} \frac{d\sigma^{hT \rightarrow h_1 h_2 X}}{dp_{T_1} dp_{T_2} dy_1 dy_2 d\Delta\phi} \quad (5)$$

where $k_1 = (p_{T_1}, \phi_1)$ and $k_2 = (p_{T_2}, \phi_2)$ are the transverse momenta of the measured hadrons and y_1 and y_2 are their rapidities. We take into account both situations where either the quark or the gluon fragments into the most forward hadron. Our results do not include convolution with fragmentation functions which should be done eventually, however we expect this has little impact on the observable we are considering here; for p_T -spectra this would be not be case.

The main features of the $\Delta\phi$ spectrum (5) are the following. First we obtain that the perturbative back-to-back peak of the azimuthal angle distribution is recovered for very large transverse momenta. Then, this back-to-back correlation is reduced by the initial state saturation effects included in our CGC approach: as the transverse momenta decrease closer to the saturation scale ($Q_s \simeq 2$ GeV), the angular distribution broadens. Finally, we notice that at RHIC energies, this does not lead to a complete disappearance of the back-to-back peak.

As can be seen from the kinematics (1), the most forward of the two particles essentially determines the value of x_h while the most central one determines the value of x_A . In order to quantitatively study the effect of the CGC evolution, the ideal situation would be to keep x_h fixed and to vary x_A . In practice, this is better realized by fixing the rapidity and momentum of the most forward particle and by varying the kinematics of the other. Note that doing the opposite would emphasize the x_h evolution of $q(x_h, \Delta)$, rather than focus on the x_A evolution of F_{x_A} . Moreover, the cross-section (2) is quite sensitive to choice of factorization scale in the quark density, so it is better to keep x_h constant. Note that varying the rapidities at fixed $y_1 - y_2$ would keep the product $x_h x_A$ constant, and would force a competition between the evolution of $q(x_h, \Delta)$ with increasing x_h and the CGC evolution with decreasing x_A .

In Figure 1a, we have studied the $\Delta\phi$ spectrum (5) in the situation in which $p_{T_1} = 3.5$ GeV, $p_{T_2} = 2$ GeV, $y_1 = 3.5$ and y_2 is varied from 1.5 to 2.5. As y_2 increases, the value of x_A decreases and the suppression of the azimuthal correlation is more important. However the effect is quite small, because the increase of the saturation scale with decreasing x_A is rather slow. In Figure 1b, we investigate the situation for which $p_{T_1} = 5$ GeV, $y_1 = 3.5$, $y_2 = 2$ and p_{T_2} is varied 1.5 GeV to 3 GeV. As p_{T_2} decreases, it gets closer to the saturation scale Q_s (which also slightly increases as x_A decreases), and the suppression of the azimuthal correlation increases. Varying p_{T_2} at fixed y_2 allows to probe the ratio p_{T_2}/Q_s over a larger range, so the effect is much bigger than when varying y_2 at fixed p_{T_2} .

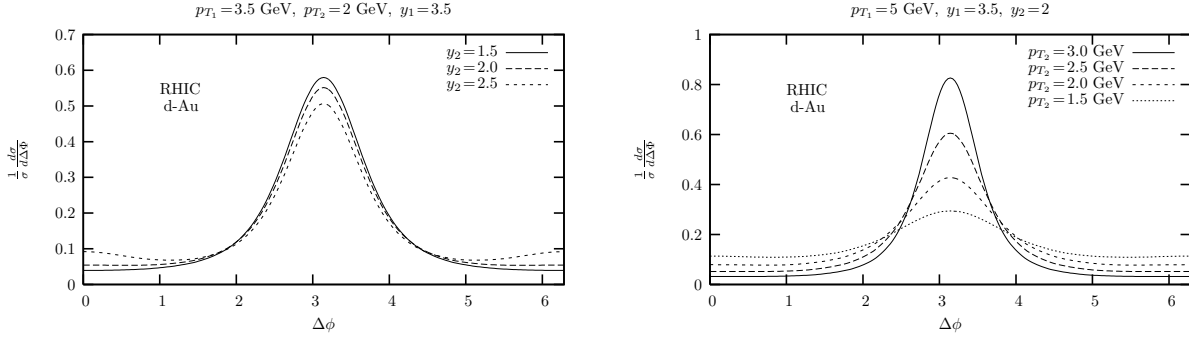


Figure 1. The $\Delta\phi$ spectrum (5) in two situations with the RHIC energy $\sqrt{s} = 200$ GeV/nucleon. In both cases, by increasing y_2 or decreasing p_{T2} , the correlation in azimuthal angle is suppressed as the value of x_A probed in the process decreases. Varying p_{T2} at fixed y_2 is much more efficient as the ratio p_{T2}/Q_s covers a larger range.

Experimental measurements of two-particle correlations in azimuthal angle have been performed in d+Au collisions at RHIC by the PHENIX and STAR collaborations. The measurements of STAR [12] with π^0 at forward rapidity and charged hadrons at mid rapidity are qualitatively consistent with a suppression of the back-to-back peak with respect to p+p collisions. By contrast, the measurements of PHENIX [13] do not show any evidence of a suppression of the back-to-back peak, but they probe values of x_A which are bigger than 0.01. It may very well be that the CGC picture breaks down for values of x_A bigger than 0.01, and it justifies our choice not to start the small- x_A evolution at a higher value.

Future measurements of azimuthal correlations between forward particles in d+Au collisions, which could be carried out at RHIC, will allow quantitative tests of the CGC. Our predictions for the fully differential cross section (2) are not directly comparable with data: once the cuts used by the experiments become available, integrations over the kinematic variables should be performed. Measurements in p+Pb collisions at the LHC would reach $x_A \sim 10^{-5}$, and could test even better the QCD evolution at small- x .

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